The Atmospheric Cherenkov Imaging Technique for Very High Energy Gamma-ray Astronomy

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Summary. The Atmospheric Cherenkov Imaging Technique has opened up the gamma-ray spectrum from 100 GeV to 50 TeV to astrophysical exploration. The development of the technique is described as are the basic principles underlying its use. The current generation of arrays of telescopes is briefly described and the early results are summarized. [1]

1 Introduction

One of the last frontiers of the gamma-ray sky is that characterized by the distribution of TeV photons. These photons can be detected relatively easily with ground-based detectors (constituting a TeV "window" in the atmosphere) and thus the detection of sources did not have to await the availability of space platforms. In practice although the technology was available at an early date, it required the impetus of gamma-ray space astronomy to justify a major effort in a new discipline. Since it concerns the highest energy photons with which it is yet feasible to map the sky, it is of particular interest to high energy astrophysics. Any source of TeV photons must be associated with a cosmic particle accelerator and of inherent interest to high energy particle physicists as well as students of the cosmic radiation.

To date almost all the observational results in the energy interval 100 GeV - 100 TeV have come from observations using the so-called "Atmospheric Cherenkov Imaging Technique (ACIT)" . Although considerable effort has been applied to the development of alternative techniques, they are not yet competitive and will not be considered here.

In this description of the Atmospheric Cherenkov Imaging Technique there will be four sections: a historical review of the ACIT with emphasis on the

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early days in which the technique was established, a brief outline of the general principles underlying atmospheric Cherenkov telescopes (ACT), a description, albeit incomplete, of the ACIT as currently used and the present generation of instruments, and a summary, which will rapidly become dated, of the current observational status of the field. More complete accounts can be found elsewhere [1],[2], [3],[4],[5].

2 Early History of the Atmospheric Cherenkov Technique

2.1 Discovery of the Phenomenon

In the Ph.D. dissertations of students studying the atmospheric Cherenkov phenomenon the first reference should be to the 1948 note by the British Nobel Laureate, P.M.S. Blackett in the Royal Society report on the study of night-sky light and aurora [6]; in that note he points out that perhaps 0.01% of the night-sky light must come from Cherenkov light emitted by cosmic rays and their secondary components as they traverse the atmosphere. In practice few students actually have read the note and indeed little attention was paid to this prediction (since it seemed unobservable) at the time. Fortunately five years later when Blackett was visiting the Harwell Air Shower array he brought his prediction to the attention of two Atomic Energy Research Establishment physicists, Bill Galbraith and John Jelley. After the visit the idea occurred to them that, while the net flux of Cherenkov light would be impossible to measure, it might be possible to detect a short light pulse from a cosmic ray air shower which involved some millions of charged particles (Figure 1).

Within a week Galbraith and Jelley had assembled the items necessary to test their hypothesis. A 5 cm diameter photomultiplier tube (PMT) was mounted in the focal plane of a 25 cm parabolic mirror (all housed in a standard-issue Harwell garbage can) and coupled to an amplifier with a state-of-the art 5 MHz amplifier whose output was displayed on an oscilloscope. They observed oscilloscope triggers from light pulses that exceeded the average noise level of the night-sky background every two minutes. They noted that the pulses disappeared when the garbage can lid was put in place and a padding lamp was adjusted to give the same current in the PMT as was observed from the night-sky [8]. Jelley noted that if the rate had been any lower than that observed they would probably have given up and gone home! [7]. It is not often that a new phenomenon can be discovered with such simple equipment and in such a short time, but it may also be true that it is not often that one finds experimental physicists of this quality!

2.2 The Power of the Technique

With the Harwell air shower array (one of the largest such arrays then in existence) in close proximity, it was easy to show that the light pulses were indeed

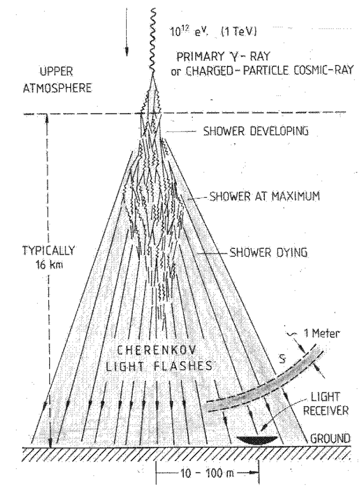

Fig. 1. Cartoon of the atmospheric Cherenkov shower phenomenon, as drawn by J.V.Jelley in 1993.

associated with air showers. In the years that followed, Galbraith and Jelley made a series of experiments in which they determined the basic parameters of the Cherenkov radiation from air showers. The account of these elegant experiments is a must-read for all newcomers to the field [9],[10]. The basic detector elements are extremely simple (Figure 2). It was realized at an early stage that the phenomenon offered the possibility of detecting point sources of cosmic ray air showers with high efficiency. Since charged primaries are rendered isotropic by the intervening interstellar magnetic fields, in practice this meant the detection of point sources of neutral quanta, i.e., gamma-ray photons or perhaps neutrons. The lateral spread of the Cherenkov light from the shower as it strikes the ground is $\approx$ 100-200 m so that even a simple light receiver of modest dimensions has an effective collection area of some tens of thousands of square meters. The fact that the light pulse preserves much of the original direction of the primary particle and that the intensity of light is proportional to the total number of secondary particles, and hence to the energy of the primary, makes the detection technique potentially very powerful.

The prediction by Cocconi [11] of a strong flux of TeV gamma rays from the Crab Nebula precipitated an experiment by the Lebedev Research Institute in the Crimea in 1960-64 [12]. Supernova Remnants and Radio Galaxies had recently been identified as sources containing synchrotron-emitting electrons which suggested that they might be gamma-ray sources. A selection of these (including the Crab Nebula) were examined with a simple ACT system which did not attempt to discriminate between air showers initiated by gamma rays and those initiated by hadrons. No sources were found but the

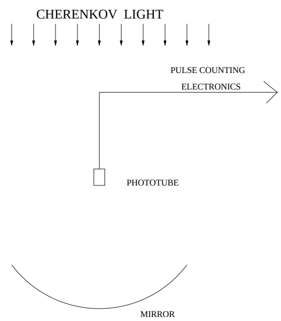

Fig. 2. The essential elements of an Atmospheric Cherenkov Detector

basic methodology involved in a search for point source anisotropies in the cosmic ray air shower distribution was defined. The technique was refined John Jelley and Neil Porter in a British-Irish experiment [13] in which the candidate source list was expanded to include the recently discovered quasars and magnetic variable stars (with null results). All these early experiments used ex-World War II searchlight mirrors (Figure 3. The first purpose-built optical reflector for gamma-ray astronomy was the Smithsonian's 10 m reflector on Mount Hopkins in southern Arizona (Figure 4). This telescope, built by Giovanni Fazio, was the first purpose-built gamma-ray telescope; it is still in use after 37 years. This again was a first generation device in which the assumption was made that there was no easily measured differences in the light pulses from gamma-ray and hadronic primaries. The motivation for this large increase in mirror area (and decrease in energy threshold) was a refined prediction of a detectable flux of gamma rays from the Crab Nebula based on a Compton-synchrotron model [14].

Although these first generation detection systems were extremely simple and exploited the ease with which gamma rays could be *detected*, they did not provide the means of *identifying* gamma rays among the much more numerous cosmic ray background Hence, until 1989 when the Crab Nebula was detected [17], there was no credible detection of a gamma-ray flux from any cosmic source.

2.3 Basic Principles

Some feel for the quantities involved in Cherenkov light emission from air showers in the energy range of interest can be seen from Table 1 based on Monte Carlo simulations by A.M. Hillas. Note that the various quantities N_{max}, the number of particles in the shower at the shower maximum and N and ρ, the number of particles and optical photons at sea level and at mountain altitude (2.3 km) scale with primary energy.

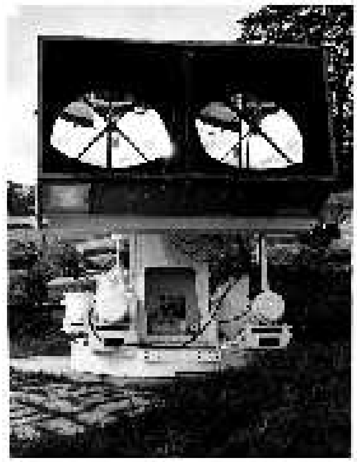

Fig. 3. The British-Irish telescope at Glencullen, Ireland c. 1964; the telescope consisted of two 90 cm searchlight mirrors on a Bofors gun mounting.

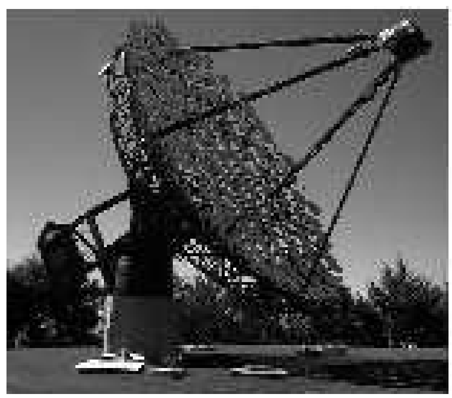

Fig. 4. The Whipple Observatory 10 m gamma-ray telescope was built in 1968; it is still in operation. It is composed of 250 glass facets, each of focal length 7.3 m.

Table 1. Shower Parameters as a Function of Energy [5]

Energy, E_γ	X_{max} g cm^{-2}	h_{max} km	N_{max}	N_{sl}	N_{mt}	ρ_{sl} ph-m^{-2}	ρ_{mt} ph-m^{-2}
100 GeV	261	10.3	130	0.04	1.4	4	8
1 TeV	346	8.4	1,140	3	60	74	130
10 TeV	431	6.8	10,000	130	1,700	11,000	1,700
100 TeV	517	5.5	93,000	4,500	36,000	16,000	19,000

The light signal (in photoelectrons) detected is given by:
$S = \int_{\lambda_2}^{\lambda_1} k\ E(\lambda)\ T(\lambda)\ \eta(\lambda)\ A\ d\lambda$
where $C(\lambda)$ is the Cherenkov photon flux within the wavelength sensitivity bounds of the PMT, λ_1 and λ_2, $E(\lambda)$ is the shower Cherenkov emission spectrum (proportional to $1/\lambda^2$), $T(\lambda)$ is the atmospheric transmission and k is a constant which depends on the shower, and the geometry.

The signal must be detected above the fluctuations in the night-sky background during the integration time of the pulse counting system, τ.

The sky noise B is given by:
$B = \int_{\lambda_2}^{\lambda_1} B(\lambda)\ \eta(\lambda)\ \tau\ A\ \Omega\ d\lambda$.
Hence the signal-to-noise ratio is essentially
$S/N = S/B^{0.5} = \int_{\lambda_2}^{\lambda_1} C(\lambda)\ [\eta\ (\lambda)\ A\ /\Omega\ B(\lambda)\ \tau]^{1/2}\ d\lambda$.

The smallest detectable light pulse is inversely proportional to S/N; the minimum detectable gamma ray then has an energy threshold, E_T given by
$E_T \propto 1/C(\lambda)\ [B(\lambda)\ \Omega\ \tau/\eta(\lambda)\ A]^{1/2}$

If S = the number of gamma rays detected from a given source in a time, t, and A_γ is the collection area for gamma-ray detection, then $S = F_\gamma(E)\ A_\gamma\ t$. The telescope will register a background, B, given by:
$B = F_{cr}\ A_{cr}(E)\ \Omega\ t$, where $A_{cr}(E)$ is the collection area for the detection of cosmic rays of energy E. The cosmic ray background has a power law spectrum:
$F_{cr}(>E) \propto E^{-1.7}$ and if we assume the gamma-ray source has the form: $F_\gamma(>E_\gamma) \propto E_\gamma{}^{-a_\gamma}$.

Then the standard deviation, $\sigma \propto S/B^{1/2} \propto E^{1.7/2-a_\gamma}\ [A_\gamma/A_{cr}]^{1/2} t^{1/2}$

The minimum number of standard deviations, σ, for a reliable source detection is generally taken as 5 [5].

3 Early Development of the ACIT

3.1 Discrimination Methods

At an early stage it was realized that while the atmospheric Cherenkov technique provided a very easy way of *detecting* gamma rays with simple light detectors, it did not readily provide a method of discriminating the light pulse from gamma-ray air showers from the background of light pulses from the much more numerous cosmic ray showers; thus the *flux sensitivity* was severely limited. Although these are isotropic, there is typically a ratio of 1,000-10,000 of cosmic rays to gamma rays recorded by the simple light detectors that were available in the two decades following the Harwell experiments. Once it was apparent that the early, very optimistic, predictions of the strength of the most obvious potential TeV sources were not to be realized, then attention turned to methods of improving the flux sensitivity of the technique. Although superficially very similar, Monte Carlo simulations of shower development and

Cherenkov light emission suggested some differences that might be exploited to preferentially select gamma rays.

These differences are listed below and illustrated in the cartoons in Figure 5:

- Lateral Spread at ground level: the light pool from gamma-ray showers is more uniform than that from cosmic ray showers. This feature is difficult to exploit since it requires numerous light detectors spread over relatively large areas; it has recently been used by the group at the Tata Institute at their Pachmari site [15]
- Angular Spread: the image of the light superimposed on the night-sky background has a more regular distribution from gamma-ray showers and is smaller and more uniform. This feature was recognized by Jelley and Porter [25] but not really exploited until some decades later. This was to prove the most powerful discriminant and to lead to the first successful credible detection of a TeV gamma-ray source [17].
- Time Structure: because the cosmic ray component contains penetrating particles (mostly muons) that survive to detector level, the duration of the light pulse can be longer. Many early versions of the ACT, particularly the Haleakala experiment [18], attempted to exploit this feature but it was not to prove very effective,
- Spectral Content: the penetrating component of cosmic ray showers is close to the light detector and its overall Cherenkov light at the detector is less attenuated in the ultraviolet; this feature was used as a discriminant in the early Whipple and Narrabri experiments of Grindlay and his collaborators [19] and in the Crimean experiments [20]. It is mostly effective when combined with other discriminants.

The Cherenkov light image has a finite angular size which can, in principle, be used to refine the arrival directing, and perhaps even to distinguish it from the images of background cosmic rays [21],[22]. However when a simple telescope with a single light detector (pixel) is used as a gamma-rays detector, this information is lost and the angular resolution is no better than the field of view of the telescope. Because the Cherenkov light images are faint and fast, it is not technically straight-forward to record them. Boley and his collaborators [23] had used an array of photomultipliers at Kitt Peak to study the longitudinal development of large air showers but these were from very energetic primaries. A pioneering effort by Hill and Porter [24], using a image intensifier system from a particle experiment, resulted in the first recorded images of Cherenkov light from air showers. However, because of the finite size of the photocathode, it was only possible to couple it to a relatively small mirror which meant that only cosmic ray primaries above 100 TeV could be detected. The potential advantages of this approach as a means of separating out the gamma-ray component were recognized [25], but since the technique was limited to energies where the attenuation of the gamma-ray

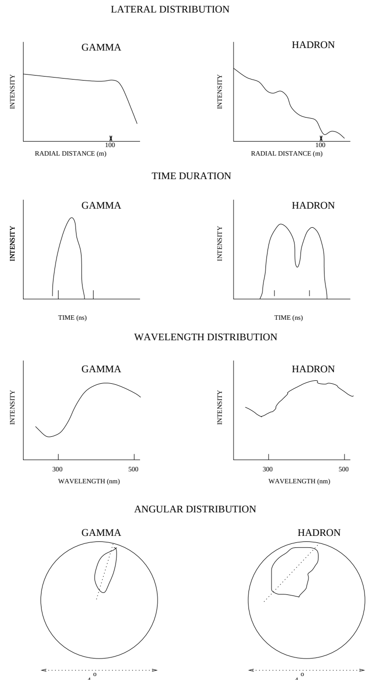

Fig. 5. Cartoon depiction of parameters used to discriminate Cherenkov light from gamma-ray and hadron air showers

flux by photon-photon pair production in intragalactic space was appreciable, this approach was not pursued.

A more practical approach was that pursued by Grindlay and his colleagues [19] in which multiple light detectors separated by distances $\approx$ 100 m were used to detect the shower maximum associated with gamma-ray showers and the penetrating, mostly muon, component from hadron showers. The latter was used as a veto to preferentially select events that were initiated by gamma rays. This "Double Beam" technique was potentially powerful but was difficult to implement with the resources available at the time; it received new life when the Narrabri Stellar Interferometer (in Australia) became available. With two large reflectors of 9 m aperture on a circular rail system, the system was ideally suited for this technique. Although some detections were reported (the Crab pulsar, the Vela pulsar and Centaurus A) [26], they have not been confirmed by later, more sensitive, observations and this technique was not pursued any further.

Activity in ground-based gamma-ray astronomy was at a low ebb in the seventies. Observations with the Whipple 10 m reflector had moved the energy threshold of the technique close to 100 GeV but this had only produced upper limits on the predicted sources. Smaller telescopes produced tentative

detections of several binaries and pulsars but these were always on the edge of statistical credibility and were not subsequently verified (for reviews of this controversial epoch of TeV gamma-ray astronomy, see [27], [28]).

3.2 The Power of the Atmospheric Cherenkov Imaging Technique

The concept of using electronic cameras consisting of matrices of phototubes in the focal plane of large reflectors to record the images of the Cherenkov light from small air showers was first suggested in a paper at a workshop in Frascati Italy [29]. Entitled "Gamma-Ray Astronomy from 10-100 GeV: a New Approach" the emphasis was on lowering the energy threshold through the use of two large reflectors separated by 100 m, each equipped with arrays of phototubes in their focal plane. The motivation to go to lower energies came from the prediction from Monte Carlo simulations that the ratio of Cherenkov light from gamma-ray showers to cosmic ray showers of the same energy drops off dramatically below 100 GeV. In this paper the physical explanation of this falloff was stated: "In a proton shower most of the Cherenkov light comes from the secondary electromagnetic cascades. Energy comes into these cascades via the production of pions by the primary and the subsequent nucleon cascade. Two thirds of the energy (approximately) goes to charged pions; they can decay to muons or undergo a collision.The latter process is a more efficient method of producing Cherenkov light; since the lifetime against decay is greater a higher energies, the chance of collisions is greater. At lower energies therefore, proportionally more energy comes off in muons whose energy may be below the Cherenkov threshold and hence the low energy showers are deficient in Cherenkov light".

The idea of using an array of phototubes with limited resolution to image the Cherenkov light rather than the high resolution offered by image intensifiers was motivated by the experience of the author using CCD detectors in optical astronomy where the resolution achieved is significantly greater than the scale of the pixels. In the paper there was little emphasis on discrimination of the primaries based on the shapes of the images although it was claimed that there would be a significant improvement in angular resolution (to $0.25°$). The use of two reflectors in coincidence was advocated to reduce the predicted muon background.

In this paper [29] the basic concept of the Cherenkov light imaging telescope was described; it consisted of an array of PMTs in the focal plane of a large reflector. The use of an array of at least two such cameras was advocated. This has been the model for all future telescopes using the ACIT. In general, in recording the Cherenkov light image from an air shower, the gamma-ray astronomer tries to characterize its nature (gamma-ray or hadron), determines its arrival direction, and gets some estimate of the primary that initiated the air shower. The geometry of the shower images is demonstrated in Figure 6. The factors that cause the observed shape and size of the image are many:

the nature of the primary particle, its energy and trajectory, the physical processes in the particle cascade (principally pair production and bremsstrahlung in electromagnetic cascades with the addition of pion production in hadron initiated cascades), Coulomb scattering of shower electrons, the effect of geomagnetic deflections of the shower particles, the distance of the point of impact of the shower core from the optic axis, the Cherenkov angle of emission, and the effect of atmospheric absorption [3]. In addition the properties of the imaging system must be completely understood: the reflectivity of the mirrors, the quantum efficiency of the light detectors as a function of wavelength, the time response of the system and the distortions introduced by the system's optics, cables, electronics and data readout.

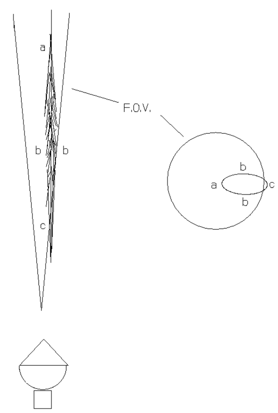

Fig. 6. The geometry of atmospheric Cherenkov imaging. On the left is a cross-section of the shower intersection with the field of view of the light detector whose inverted image plane is seen on the right.

Fortunately all of these factors are amenable to calculation or measurement. The physics of the various processes involved in the shower development are well known and Monte Carlo methods can be used to estimate the expected values from particular primaries. However since fluctuations play a major role in such development the expected values cover a range of possibilities and identification must always be a statistical process. It is relatively easy to predict the properties of the gamma-ray initiated showers; it is more difficult to predict the expected properties of the background which is mainly from charged cosmic rays. While every attempt is made to estimate both signal and background, it is usually found that the background contains some unpleasant surprises; hence while the gamma-ray detection rate can be reliably predicted, the efficiency of the identification of the gamma-rays from the more numerous background requires the system to be actually operated in observations of a known source. Since the background is numerous and constant, its

properties can be readily modeled from empirical databases. There is an irreducible background from hadron showers which develop like electromagnetic cascades (most of the energy goes into a π^o in the first interaction) and from the electromagnetic cascades produced by cosmic electrons (whose fluxes in the range of interest are 0.1 - 0.01% of the hadron flux).

3.3 The First Source

When the imaging systems first went into operation it was not immediately obvious how the images should be characterized and discriminated from the background. There were no credible sources and Monte Carlo calculations were still being developed and were untested. The first such calculations available to the Whipple Collaboration indicated that fluctuations might effectively rule out any discrimination and did not encourage the development of sophisticated analysis techniques. The first Whipple camera had 37 pixels, each of 0.25° diameter [30]. A relatively simple image parameter, *Frac2*, defined as the ratio of the signal in the two brightest pixels to the total light in the image, was developed empirically and led to the first indication of a signal from the Crab Nebula [31], [32]. This simple parameter picked out the compact images expected from electromagnetic cascades but did not provide any information on the arrival direction (other than that it was within the field of view of the detector). However the application of the same selection method on putative signals from the then popular sources, Cygnus X-3 and Hercules X-1, did not improve the detection credibility and initially cast doubt on the effectiveness of *Frac2* as a gamma-ray identifier.

Since the images were roughly elliptical in shape, an attempt was made to quantify the images in terms of their second and third moments [33]. However this was not applied to gamma-ray identification until Hillas undertook a new series of Monte Carlo calculations [34]. These calculations predicted that gamma-rays images could be distinguished from the background of isotropic hadronic images based on two criteria: the physics of the shower development was different leading to smaller and better defined ellipses for gamma rays and that the geometry of image formation led to all images coming from a point source on axis having their major axes intersecting the center of the field of view. Fortunately the first property aids the definition of the second and provides potentially very good angular resolution. Hillas [34] defined a series of parameters which included the second moments (*Width* and *Length*), the parameter *Dist* which measures the distance of the centroid of the image from the optic axis, and *Azwidth* which measures the projected width of the image on the line joining the centroid to the center of the field of view. Later *Alpha*, the angle between this line and the major axis was added as was *Asymmetry*, the third moment. *Azwidth* was particularly simple; it is easy to use and proved to be very effective as it combined discrimination based on image size (physics) and arrival direction (geometry) and led to the first definite detection of a point source of TeV gamma-rays. In general multiple parameter selections

were made. The parameters were first defined in Monte Carlo calculations but once the standard candle of the Crab Nebula was established [17], optimization was made on the strong and steady Crab signal to preferentially select gamma rays. This optimization led to an analysis package called Supercuts [35], which proved to be extraordinarily robust, and in various forms, was the basis of the data analysis used by the Whipple Collaboration to detect the first AGN [36],[37], [38],[39],[40]. Other groups have defined different parameters and analysis schemes but the basic methodology is the same.

4 ACT Observatories

4.1 Third Generation Observatories

By 1996 the ACIT was judged to have been very successful and a number of groups made plans for a third generation of the ACTs. The limitation of a single telescope was easily seen from the results obtained using the Whipple telescope and camera [41]. At low trigger thresholds it was impossible to distinguish low energy gamma-ray events from the much more numerous background of partial muon rings (arcs). Despite intense efforts with sophisticated analysis methods it was clear that the discrimination threshold was a factor of 2-3 above the trigger threshold. Hence although the fundamental threshold was $\approx$ 200 GeV, the effective threshold was $\approx$ 400 GeV. Since the muon Cherenkov emission is essentially a local phenomenon, this background is easily eliminated by demanding a coincidence with a second telescope separated from the first by a minimum distance of 50 m [29]. In fact the HEGRA experiment had already demonstrated [42] the power of an array of small imaging telescopes to improve the angular and energy resolution of the ACIT; at the threshold energies of these telescopes the muon background was not a problem.

Thus it was apparent that the next generation of the ACIT would involve arrays of reflectors with apertures in excess of 10 m, with better optics, with more sophisticated cameras, and with data acquisition systems capable of handling high rates. Such systems required an investment that was almost an order of magnitude greater than the previous generation of detectors (but the flux sensitivity was to improve by a similar factor (Figure 7)). Of necessity the number of people involved in each experiment would be so large ($\approx$ 100) that the new collaborations would be more in line with the numbers of scientists found in particle physics experiments than in typical large astronomical projects.

4.2 The Power of ACT Arrays

ACTs arrays can be discussed under the headings of improvements offered in energy threshold, energy resolution, angular resolution and background

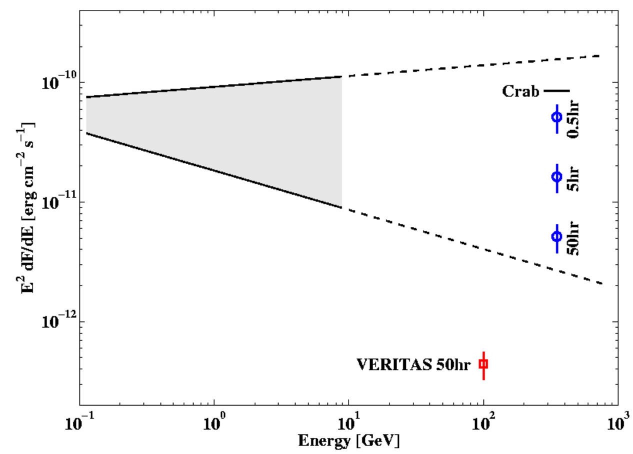

Fig. 7. Integral flux sensitivity for various integration times for the Whipple telescope (unlabeled points) and for the projected VERITAS array [46]. The dotted lines are the extrapolated energy spectra from sources detected by EGRET.

discrimination. A good discussion can be found in [2]. A typical array provides multiple images of a single event as seen in Figure 8.

Energy Threshold: The basic quantities involved in determining the energy threshold of an ACT are given above in Section 2.3 and are fairly obvious: the mirror area should be as large as possible and the light detectors should have the highest possible quantum efficiency. To the first approximation (as demonstrated in [12]) it does not critically depend on how the mirror area is distributed, i.e., a cluster of small telescopes in close proximity operated in coincidence is the same as if their signals are added and is approximately the same as that of a single large telescope of the same total mirror area. Practical considerations tend to dominate: coincidence systems are more stable, the cost of telescopes scales as the (aperture)$^{2.5}$, the relative cost of multiple cameras on multiple small telescopes versus the cost of a single camera on a large telescope, etc. However the simplest way to get the lowest energy threshold is to go for a single large telescope (although this may introduce other problems).

Angular Resolution: Angular resolution is important not only for reducing the background and identifying a potential source but also for mapping the distribution of gamma rays in the source. Stereoscopic imaging, the simplest form of "array" imaging, offers the immediate advantage of improving the angular resolution. This principle was established with the use of just two telescopes with a separation of $\approx$ 100 m, i.e., with the two telescopes within the light pool of the Cherenkov light pool, $\approx$ a circle of diameter 200 m. The greater the separation, the better the angular resolution but increasing the separation beyond 100 m begins to reduce the effective gamma-ray collection area. A simple array of imaging ACTs can provide a source location of $\approx 0.05°$

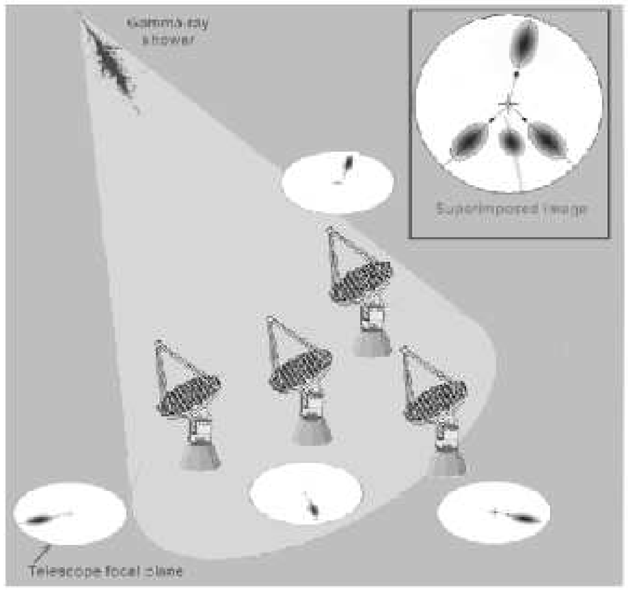

Fig. 8. Cartoon showing response of array of four detectors to air shower whose axis is parallel to the optical axes of the telescopes and some 30 m displaced from the center of array. (Figure courtesy of P.Cogan)

for a relatively strong source with angular resolution of $\approx 0.1°$ for individual events. This is a factor of two improvement over that for a single telescope. An angular resolution of an arc-min or better appears feasible.

Background Discrimination: Multiple views of the same air shower from different angles obviously improves the signal-to-noise ratio when the images are combined. However in reducing the background of hadronic events the gain is not as large as might appear at first glance. Hadronic showers which develop like typical showers are easily identified and rejected, even in a single telescope. More subtle are the hadronic events which develop like an electromagnetic cascade (an early interaction channels much of the energy into an electron or gamma ray). Such events cannot be identified not matter how many views are provided on the cascade development. Similarly the cascades initiated by cosmic electrons are an irreducible background. However the array approach does completely remove the background from single local muons and the improved angular resolution narrows the acceptable arrival directions.

Energy Resolution; The Cherenkov light emitted from the electromagnetic cascade is to a first approximation proportional to the energy of the initiating gamma ray (Table 1). However with a single ACT there is no precise information as to the impact parameter of the shower axis at ground level. Since the intensity of the Cherenkov light is a function of distance from the shower axis,

the lack of information on this parameter is the limiting factor in determining the energy of the gamma ray. The energy resolution of a single imaging ACT is $\approx$ 30-40%. With an array the impact parameter can be determined to $\approx$ 10 m and the energy resolution can be reduced to 10%.

4.3 The Third Generation Arrays

This third generation of ACTs has seen the formation of four large collaborations formed to build arrays of large telescopes: a largely German-Spanish collaboration that is building two 17 m telescopes on La Palma in the Canary islands (MAGIC) [47] (Figure 9): an Irish-British-Canadian-USA collaboration that is building an array of four 12 m telescopes in Arizona (VERITAS) [44]; an Australian-Japanese collaboration that has built four 10 m telescopes in Australia (CANGAROO-III) [45]; a largely European collaboration that has built an array of four 12 m telescopes in Namibia (HESS) [43] and plans to add a fifth telescope of 28 m aperture at the center of the array (Figure 10). The fact that two of the arrays are in each hemisphere is somewhat fortuitous but ensures that there will be good coverage of the entire sky and that all observations can be independently verified. The principal properties of the four arrays are summarized in Table 2.

The sensitivity of these new arrays is probably not dissimilar but only HESS has demonstrated what it can achieve in the actual detection of known sources. With the second generation of ACTs (Whipple, HEGRA), it was possible to detect a source that was 5% of the Crab Nebula in 100 hours of observation. With HESS this is reduced to one hour and in principle in 100 hours it should be possible to detect a source as weak as 0.5% of the Crab. HESS has also demonstrated an energy resolution of 10% and an angular resolution of an arc-min.

Table 2. Next Generation ACT Arrays

Experiment	Location	Elevation km	Telescopes	Aperture m	Pixels /camera	Energy GeV
CANGAROO-III	Woomera, Australia	0.2	4	10	577	50?
HESS	Gamsberg, Namibia	1.8	4	12	960	50
MAGIC	La Palma, Spain	2.3	2	12	577	20?
VERITAS	Arizona, USA	1.8	7	12	499	50

4.4 Hardware Considerations

Location: Although it is generally accepted that ACTs gain sensitivity by going to higher elevations, practical considerations have to date limited such

Fig. 9. The 17m aperture telescope, MAGIC, which was completed in 2003 and is now in operation on La Palma in the Canary Islands, Spain.

Fig. 10. The HESS array of four 12m aperture telescopes; it has been in full operation in Namibia since 2004.

observatories to quite moderate elevations by astronomical standards. The CANGAROO-III observatory is near sea level and the other three observatories are at conventional optical astronomical elevations (< 2.5 km).

Number and Configuration: The minimum number of telescopes is more than two. Three is optimum but four gives some redundancy and is usually the preferred number. Monte Carlo simulations indicate that the telescope arrays are somewhat insensitive to the precise configuration of the telescopes and to the exact separation. The HESS telescopes have a square configuration of side 100 m. The CANGAROO-III telescopes are in a diamond-shaped configuration with characteristic spacing of 120 m. Three of the VERITAS telescopes form a equilateral triangle with a fourth at the center; the distance from it to each of the corners is 80 m.

Light Detectors: It is remarkable that the same light detectors are in use in all of this generation of experiments as were used in the initial experiments of Jelley and Galbraith fifty years ago. The remarkably robust PMT tube is fast, has a high gain and is reasonably efficient; however it requires operation at high voltages, has quantum efficiencies less than 25% and is easily damaged by exposure to bright light. For many years it has appeared that it is about to be replaced by a new technology device with higher quantum efficiency. However as of this date no such device has yet been used in any application to detect Cherenkov light pulses from air showers. Hence the practical application of such devices to the rather demanding cameras on ACTs still seems some way off.

Optics: Mirror area is a critical factor in ACTs. It is not practical to use a single large mirror because the cost of producing and supporting it is so large (although the CANGAROO group used the 8m Subaru optical telescope in Hawaii for a short period). Mirror area therefore is usually achieved by the use of multiple facets, which are relatively light, are economical to produce, can be recoated easily and can be close packed to mimic a single mirror surface. However the facets introduce aberrations and require careful alignment. The facets can be circular (HESS, CANGAROO), square (MAGIC) or hexagonal (VERITAS); the circular shape is inefficient but is cheaper to produce. Glass is still the generally preferred material (HESS, VERITAS) with the optical figure formed by slumping, then grinding and polishing; MAGIC uses diamond-machined aluminum mirrors and CANGAROO-III uses composite plastic mirrors which, although lighter, do not have the optical quality of glass mirrors. The aluminum coating on the latter must be overcoated with quartz (HESS) or anodized (VERITAS).

Positioners: ACTs have not used equatorial mounts. The MAGIC and HESS experiments have utilized positioners with the alt-azimuth design used in some large radio telescopes and solar energy devices; the elevation motion is a large circular gear while the azimuth motion is rotation around a large track that is the diameter of the aperture. The CANGAROO-III and VERITAS telescopes use the conventional alt-azimuth mounting used in the Whipple 10 m reflector and in many radio telescopes and communication devices.

5 Observation Summary

VHE gamma-ray astronomy is now a fast moving field and the observational picture is changing quickly as the new generation of telescopes comes on-line. The HESS observatory has been particularly productive and it is expected that it will shortly be joined by CANGAROO-III, MAGIC and VERITAS. The catalog of current sources listed in Table 3 is dominated by HESS results; it is a measure of their success that they have been able to announce a new discovery every month and no end appears to be in sight. As in any rapidly developing field this catalog will rapidly become out of date; it is current as of July, 2005 and is quite different from that presented at the Heraeus school twelve months earlier. Entries to the table are based on published results in refereed journals. The first column gives the catalog name for the source, the second the conventional source name (where there it is a known object), the third is the source type, where known, the fourth the group responsible for the discovery, the fifth the date of discovery, and finally the significant discovery reference. A feature of this new catalog is that not only does it contain many new sources compared with previous listings [5], but it also contains some significant omissions. Several sources, including TeV 0047-2518 (NGC 253), TeV 0834–4500 (Vela), TeV 1503-4157 (SN1006) and TeV 1710-2229 (PSR 1706-44), have not been verified by the more sensitive observations by HESS. All four sources were reported with good statistical significance by the CANGAROO group and it is a matter of concern in the VHE gamma-ray community that these sources were reported and published in refereed journals. It is apparent that there were unknown systematic errors in the data taking and/or the analyzes were not independently verified within the large CANGAROO collaboration. It is unfortunate for the discipline that these important sources, whose discovery had been greeted with some excitement, have been red herrings and have decreased the credibility of other legitimate discoveries. Since many of these CANGAROO pseudo-sources were reported to have steep spectra, one possible explanation for the data was unevenly matched ON and OFF fields and hence systematic biases in the datasets.

It should be noted that a few of the sources listed in Table 3 still do not have the statistical significance and independent verification that one would like. These include TeV 0219+4248 (3C66a), TeV 1121-6037 (Centaurus X-3), TeV 2203+4217 (BL Lac) and TeV 2323+5849 (Cassiopeia A).

The most complete catalog of sources is that of blazars of the HBL classification; these are those whose synchrotron spectrum peaks in the X-ray part of the spectrum. All of these detections are well-established; their principal properties are listed in Table 4 which is updated from that given in [49]. Taken together these sources form the basis for a new exploration of relativistic particles in AGN jets.

Table 3. Source Catalog c.2005

TeV Catalog Name	Source	Type	Discovery Date	Group	Reference
TeV 0219+4248	3C66A	Blazar	1998	Crimea	[50]
TeV 0535+2200	Crab Nebula	SNR	1989	Whipple	[17]
TeV 0852-4622	Vela Junior	SNR	2005	HESS	[51]
TeV 1121-6037	Cen X-3	Binary	1998	Durham	[52]
TeV 1104+3813	Mrk 421	Blazar	1992	Whipple	[36]
TeV 1231+1224	M87	Radio Gal.	2003	HEGRA	[53]
TeV 1259-63	PSR1259-63/SS2883	Binary Pulsar	2005	HESS	[61]
TeV 1303-631?	Unidentified	SNR?	2005	HESS	[62]
TeV 1429+4240	H1426+428	Blazar	2002	Whipple	[54]
TeV 1514-5915	MSH15-52	PWN	2005	HESS	[56]
TeV 1614-5150	Unidentified	?	2005	HESS	[55]
TeV 1616-5053	PSR1617-5055?	Pulsar	2005	HESS	[55]
TeV 1640-4631	G338.-0.0	SNR	2005	HESS	[55]
TeV 1654+3946	Mrk 501	Blazar	1995	Whipple	[37]
TeV 1712-3932	RXJ1713.7-39	SNR	1999	CANGAROO	[58]
TeV 1745-2900	Gal. Cen.	AGN?	2005	HESS	[59]
TeV 1747-2809	SNR G0.9+0.1	SNR	2005	HESS	[55]
TeV 1804-2141	G8.7-0.1/W30	SNR	2005	HESS	[55]
TeV 1813-1750	Unidentified	?	2005	HESS	[55]
TeV 1825-1345	PSR J1826-1334?	Pulsar	2005	HESS	[55]
TeV 1826-148	LS 5039	Microquasar	2005	HESS	[56]
TeV 1834-0845	G23.3-0.3/W41?	SNR	2005	HESS	[55]
TeV 1837-0655	G25.5+0.0?	SNR	2005	HESS	[55]
TeV 2000+6509	1ES1959+650	Blazar	1999	Tel.Ar.	[60]
TeV 2005-489	PKS 2005-489	Blazar	2005	HESS	[63]
TeV 2032+4131	CygOB2?	OB assoc.	2002	HEGRA	[65]
TeV 2159-3014	PKS2155-304	Blazar	1999	Durham	[64]
TeV 2203+4217	BL Lacertae	Blazar	2001	Crimea	[67]
TeV 2323+5849	Cas A	SNR	1999	HEGRA	[68]
TeV 2347+5142	1ES2344+514	Blazar	1997	Whipple	[39]

6 Conclusion

It is clear that TeV sources are ubiquitous and a powerful tool for exploring the relativistic universe. Despite this rich catalog of sources there is still not unambiguous evidence for the source of the hadronic cosmic radiation; it is possible to explain all the observed TeV gamma rays as coming from electron progenitors. Hence despite the dramatic advances that the new catalogs of TeV sources represent, the origin of the cosmic radiation remains a mystery.

Although the cement is hardly dry in the foundations of the third generation of ACTs there is already active discussion of how the fourth generation

Table 4. TeV Blazars

Source	Class	Redshift	F_γ (mean) > 100 MeV $10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	F_γ (Det.) $> E_{peak}$ $10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	E_{peak} (Det.) GeV
Mrk 421	BL Lac(HBL)	0.031	13.9	15.0	500
H1426+428	BL Lac(HBL)	0.129	U.L.	20.4	280
Mrk 501	BL Lac(HBL)	0.034	U.L.	81	300
1ES1959+650	BL Lac(HBL)	0.048	U.L.	29.4	600
1ES2005-489	BL Lac (HBL)	0.071	U.L.	6.9	200
PKS2155-304	BL Lac(HBL)	0.117	13.2	42.0	300
1ES2344+514	BL Lac(HBL)	0.044	U.L.	11.0	350

might be configured. It appears that in the energy range from 100 GeV to 100 TeV there will be no technique, either in space or on the ground, can hope to compete with the ACIT in terms of flux sensitivity to point sources in the next decade (Figure 11). It is technically possible to build VHE observatories that will have flux sensitivities in the 100-1000 GeV range that will exceed those currently achieved by a factor of ten. These new arrays will be particularly sensitive to transient emission and hence the focus may be on cosmological studies. Several concepts involve ACTs that can reach down to energies as low as 10 GeV. There do not appear to be any space missions on the drawing boards that would offer a major extension to the sensitivity of GLAST. At a recent workshop [69] several interesting concepts for a new generation ACT were proposed; the ground-based gamma-ray community has not yet coalesced to a single concept. This consolidation of manpower and resources will be surely necessary if a project of this magnitude is to be realized. However all are agreed that a new generation observatory is both necessary and feasible.

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Fig. 11. A photomontage showing the VERITAS observatory; this will have four telescopes of 12 m aperture and will come on-line in 2005.

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